Assessment of Winding Deformation in Power Transformer using SFRA and Numerical Techniques

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Assessment of Winding Deformation in Power Transformer using SFRA and Numerical Techniques

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based on research carried out

Under the supervision of

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May, 2016

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Supervisor's Certificate

This is to certify that the work presented in the thesis entitled *Assessment of Winding Deformation in Power Transformer using SFRA and Numerical Techniques* submitted by *Ashwini Bhujangrao Gaikwad*, Roll Number 214EE4245, is a record of original research carried out by her under my supervision and guidance in partial fulfillment of the requirements of the degree of *Master of Technology* in *Electrical Engineering*. Neither this thesis nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

Dr. S. Gopalakrishna

Dedicated

To my loving family,

Teachers & my well wishers

Ashwini Bhujangrao Gaikwad

Declaration of Originality

I *Ashwini Bhujangrao Gaikwad*, Roll Number *214EE4245 hereby* declare that this dissertation entitled*, "Assessment of Winding Deformation in Power Transformer using SFRA and Numerical Techniques"* presents my original work carried out as a doctoral student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections "Reference" or "Bibliography". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

May 20, 2016

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ABSTRACT

In Modern power system the Power transformer is one of the most costly equipment installed in power system. Power transformers are designed to withstand a variety of stresses and mechanical forces during their service life. Abnormal forces generated during short-circuit event (occurring near to a transformer) is the main reason behind the deformation of winding and core. Hence, special care to be taken during installation of a new power transformer in an electrical substation. Studies Shows several winding deformations, which includes tilting and bending of conductors and inter-disc fault. These three faults are examined in terms of their severity of damage and location of the fault. Statistical analysis is applied to determine the overall condition of the winding.

In order to contribute to diagnose these faults sweep frequency response analysis (SFRA) is a powerful and highly sensitive diagnostic method of measurement on several common winding deformations including winding deformations and displacements, shorted turns and open windings, loosened or broken clamping structures, core connection problems, partial winding collapse, faulty core grounding, core movements and hoop buckling and explores a new potential diagnostic scheme of FRA Moreover, because FRA relies on graphical analysis, it needs an expert person to analyze the results as so far, there is no standard code for FRA interpretation worldwide. To provide such a reference curve, some manufacturers now carry out SFRA tests on all new transformers before they are dispatched to site. But FRA results are graphical in nature and require trained experts to interpret test results.

The work reported discusses numerical-criteria based evaluation techniques. Persons not familiar with interpreting the FRA results can apply the evaluation criteria. The various criteria help in deriving proper conclusions. By evaluating Correlation Coefficient (CC),Standard Deviation (SD) and Absolute Sum of Logarithmic Error(ASLE),Comparative Standard Deviation (CSD),Absolute Difference (AD), Min Max Ration (MM), Mean Square Error (MSE) it is possible to discriminate between defective and non-defective windings

easily. Among these numerical techniques CCC, SD and ASLE are more effective way of finding deformation in windings.

Keywords: SFRA; Numerical Techniques; Short Circuit Events; Electromagnetic Forces

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List of Abbreviation

SFRA	Sweep Frequency Response Analysis
SD	Standard Deviation
ASLE	Absolute Sum of Logarithmic Error
CCC	Cross Correlation Coefficient
AD	Absolute Difference
CSD	Comparative Standard Deviation
MSE	Mean Square Error
MM	Min Max Ratio

List of Symbols

B	Flux density
F	Force
I	Current
L	Winding length
B_X	Radial flux density
B_y	Axial flux density
J	Current density
F_x	Radial force
F_y	Axial force
NI	Ampere turns
μ_0	Absolute permeability
B_{gp}	Air gap flux density
H_w	Height of winding in meters
$\mathrm{D_m}$	Mean diameter
$\mathrm{R_s}$	Series resistance between adjacent sections of helical coil
$\mathrm{R_g}$	Resistance between section and ground
$\mathrm{C_g}$	Capacitance between section and ground
$\mathrm{C_s}$	Capacitance of section
$\mathrm{L_{ii}}$	Self-inductance of i^{th} section
$\mathrm{M_{i-j}}$	Mutual inductance between i^{th} and j^{th} section of the coil
X(i)	i^{th} element of the reference fingerprint
Y(i)	i^{th} element of measured frequency response
N	Total number of samples in the frequency response
$\mathrm{n_1}$	Number of turns of first coil
$\mathrm{n_2}$	Number of turns of second coil
$\mathrm{I_{hv}}$	HV winding Current
$\mathrm{I_{lv}}$	LV winding Current

V_l'	Line voltage of primary winding
V_l	Line voltage of secondary winding
P	MVA rating of the transformer
Z_S	Impedance of measurement cable
Z_T	Impedance of transformer winding
S	Signal
R	Reference measurement
T	Test measurement
S	Rated power per limb in kVA
H_W	Height of winding in meters
Z_{PU}	Impedance in per unit
F	Frequency (Hz)

Chapter 1

Introduction

1.1 Introduction

Transformer is a key component in power transmission line as it transfers power from one electrical circuit to other at constant frequency. There are various reasons by which transformer may get damaged such as ageing, during transportation windings may get deformed and also due to thermal, electrical and mechanical stresses. Mainly this stresses are causes due to short circuit problem. During short circuit event, magnitude of current is very high compared to normal current. Interaction of current and mutual flux (flux linking both low voltage winding and high voltage windings of transformer) leads to production of high electromagnetic forces .This forces tends to deform the transformer winding. Windings may deform in two directions axial deformation and radial deformation respectively. Axial deformation causes due to forces acting in axial direction and radial deformation causes due to forces acting in radial direction. Due to deformations winding get disturb, insulation damages and parameter changes. If these deformations are unnoticed for long time, it may lead to permanent failure of transformer. That's why there is need of constant assessment of winding deformation in transformer for safe operation, better maintenance and improves reliability.

SFRA technique is used to detect deformation in winding. In this graphically deformation is measured by observing deviation of measured response from reference response. More measured response deviates from reference response represents more deformation. Trained person is needed to observe small deviation properly. Observation is solely depends on the experience of the person who observes deviation.

Numerical techniques are used to make SFRA observation more clear and easy to understand. In this deviations are indicated in numerical value which is easy to understand by inexperienced person also. Various techniques are mention in this paper such as cross correlation coefficient (CCC), standard deviation (SD), absolute sum of logarithmic error (ASLE), absolute difference (AD), mean square error (MSE), min max ratio (MM) and comparative standard deviation (CSD). Every technique is good and has its own advantage/ importance over other. But among these techniques CCC, SD and ASLE are better to observe deviation correctly.

1.2 Literature Review

Manufacturer makes power transformer to work efficiently. They make it with lot of care and attention. But the same transformer when customer receives may or may not be in same condition as it was dispatched mechanical stress developed during transportation may disturb winding. The main reason behind the winding deformation is frequent [18] short circuit events high current will flow in winding [1-3]. Interaction of current and flux density will produce electromagnetic force due to this force stress is exerted radialy and axially. Due to frequent short circuit event and deformation short circuits withstand capacity of winding will get reduced. Other effects are spiraling of conductor, conductor tilting, bending of radial spacers, forced buckling and free buckling of conductor [12]. Electromagnetic forces are proportional to square of current flowing through winding which is dangerous during short circuit condition.

Due to deformation in winding parameter such as resistance, capacitance and inductance of the winding will get change which leads to change in efficiency. In worst case if winding get more deformed then it is send back to manufacturer for rewinding that’s why there is need of proper diagnosis of winding condition to avoid failure and damage of it and for smooth operation of transformer.

Short circuit reactance measurement is one of the methods to diagnose the mechanical integrity of the winding but because of its low sensitivity [5] and as it can’t be performed on existing transformer it is not that commonly used [4]. To diagnose the winding deformation Low Voltage Impulse [20] method is widely used .its first application was made in 1966in Poland. LVI method has its limitation frequency. The transfer function obtained from this method is restricted in frequency [10] range from 10 kHz to 1MHz.

SFRA is an emerging technique to detect winding. SFRA overcomes all limitations of LVI and short circuit reactance method. This method doesn't have any frequency restriction limitation, more sensitivity, better resolution and can be performed on existing transformer without opening it [10].

Every transformer has its own unique signature. Due to change in parameter which was caused because of deformation, unique signature of transformer will change. if mechanical integrity of winding changes it affects its electrical response which leads to change in signature of winding. [9] In SFRA reference finger print is compared with the measured response[18]. Deviation from the reference signature will indicate the extent of deformation in the winding.

A helical test coil designed with specification given in paper [17] used as benchmark coil. By varying the coil dimensions, change in impedance has been calculated. SFRA analysis done with changed parameter. SFRA test performed on 440 MVA transformer to diagnose deformation and fault in winding [18].

SFRA is graphical comparison method .Two graphs reference and measured response is compared. Comparison is solely depends on the skill of the person as it is visual inspection method. To avoid human error numerical technique is best solution. Numerical values are obtained directly. Deviations are measured numerically which makes deviation observation more clear and easy to understand to non skillful person also. The numerical techniques used in this paper are cross correlation coefficient [17], standard deviation, absolute sum of logarithmic error, min max ratio, absolute difference, root mean square, [15] comparative standard deviation. [10].Each numerical technique has its own importance. ASLE is better in some case while SD is better in detecting deviation [21]. To observe deformation only one numerical technique is not enough because uniqueness of each method Among all methods CCC, SD, ASLE are best to detect winding deformation.

1.3 Motivation

Day by day electrical supply demand is increasing. Transformer plays vital role in transmission line. Special attention is needed for maintenance, safe operation and reliability of transformer. Winding get deformed during short circuit event due to production of heavy electromagnetic force. These forces are generated due to interaction of short circuit current (5-8 times of rated) and magnetic flux density vector. Because of force mechanical integrity of transformer will change leads to change in electrical parameters (R, L, and C).

There are various method to detect deformation but among all SFRA is better because of its sensitivity, better resolution, repeatability and overcomes limitations of all other methods. SFRA is graphical method; it needs trained person to observation deviation .Numerical techniques are statistical approach to observe SFRA more clearly and simple. With these techniques untrained person can also detect deformation.

1.4 Objective

- 2D modeling of transformer and determination of forces
- Design a coil to study winding deformation
- Create deformation axially and radialy to obtain changed parameters
- Obtain SFRA using healthy and changed parameters
- Comparison of healthy coil and deformed coil
- Apply numerical techniques on SFRA to get deviation in graph in numerical values

1.5 Thesis Layout

Chapter 1 consists of a brief overview of the topic, literature review, motivation, objectives and layout of thesis.

Chapter 2 consists of description of winding deformation, its causes, how deformation occurs, axial deformation and radial deformation along with its effects and failure mode

Chapter 3 consists of description of test coil model, modeling of coil in matlab with axial and radial deformation is described, also shown how parameters changes with each coil deformed from 1% to 7% axially and radialy

Chapter 4 describes about SFRA, results of SFRA obtained from matlab coding and describes SFRA test performed on 500kVA transformer

Chapter 5 describes about numerical techniques, formulae, verified deviation with numerical values

Chapter 6 consists of summary of the work carried out, future scope of the work and references

Chapter 2

Winding deformation

2.1 Introduction

Winding deformation in range is acceptable but above its range winding need to rewind again. Among all other causes short circuit event affects winding more and deformed it axially and radialy. Interaction of high current during short circuit with magnetic field will generate force which will deformed winding axially and radialy. Computations of generated forces are essential to decide short circuits withstand capacity of transformer so that required precaution can be taken to avoid damage of winding and design and manufacturing process can be improved. Power transformer is complex network of R, L, C parameter. Computation of forces with analytical approach is complex procedure. Computation of forces for complex geometry of power transformer is done with FEM (finite element method) based Magnet software.

2.2 Causes of deformation

Power transformer is integral part of power system. It plays vital role in power transmission. Its failure is costly event so special care has to be taken for its maintenance. There are several tests such as type test, routine test are performed on transformer by manufacturer to check its reliability and performance. Sometime the same good condition transformer dispatched from the manufacturer may or may not in good condition when customer receives it. This is because mechanical stresses develop during transportation may cause deformation in winding. Ageing of insulation can also affect the firmness of winding wound on the core. Due to ageing or damage of insulation may lead to displacement of winding from its position. Mainly Short circuit event is major reason behind winding deformation.

2.3 How deformation occurs

High magnitudes of currents about 5 to 10 times of normal current are generated due to short circuit events occur in the transformer. The interaction of the high magnitude current and leakage flux density result in extreme electromagnetic forces to act on the winding. The equation of electromagnetic force is given as

$$F = LI \times B \tag{2.1}$$

In 2D analysis of forces with taking current density in z axis, at any point leakage flux density (B) can be resolved into two components i.e. one in axial direction (By) while other in radial direction (B_X). Thus the interaction of axial leakage flux density (By) with current density (J) will generate radial force (F_x) and the interaction of radial leakage flux density (B_X) with current density (J) will generate axial force(F_y).

Axial deformation is given as

$$F_y = \iint (J \times B_X)dxdy \tag{2.2}$$

Radial deformation is given as

$$F_x = \iint (J \times B_Y)dxdy \tag{2.3}$$

Using Fleming's left hand rule the direction of generated forces is determined. Forces experienced by a winding are proportional to the square of the short circuit current and forces are unidirectional and pulsating in nature. The generated electromagnetic force due to short circuit is resolve into radial forces and axial forces as these two forces exert different kind of stress on winding and have different modes of failures.

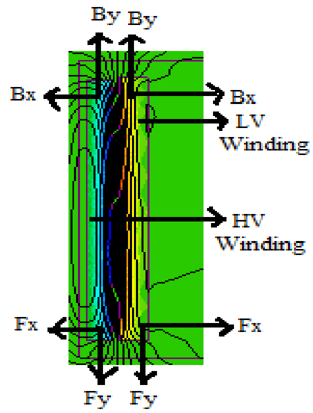

Fig. 2.1 Axial forces and radial forces on transformer winding

2.3.1 Axial deformation

The generated axial forces are directed towards the center of winding and outwards of the winding but axial forces directed towards the center of winding is more compared to forces exerted outwards. At the winding ends axial forces are higher. As the inner winding is near to limb will experience more compressive force compared to the outer winding. In the absence of detailed analysis, it can be assumed that 25 to 33% of force is taken by the outer winding, and the remaining 75 to 67% is taken by the inner winding

The total axial compressive force acting on the inner winding and outer windings taken together with an asymmetry factor of 1.8 is given as

$$F_y = \frac{50.8 \times S}{Z_{pu} \times H_w \times f} \tag{2.4}$$

The reasons behind higher value of radial field and consequent axial forces are: mismatch of ampere-turn distribution between LV and HV windings, tapping in the winding, unaccounted shrinkage of insulation during drying and impregnation processes, etc

If the windings are not placed symmetrically with respect to the center-line then generated axial force will create more asymmetry in winding and will also increase end thrusts on the clamping structure. Dimension control is strictly followed during processing and assembling of windings so that windings are placed symmetrically otherwise misalignment of magnetic centers of windings or even a small axial displacement may cause enormous axial forces.

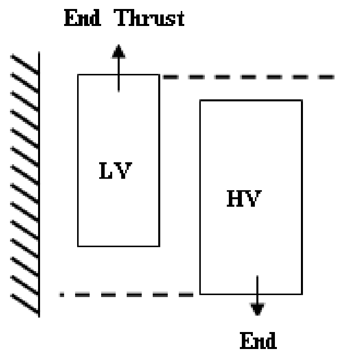

Fig. 2.2 Axial asymmetry

2.3.2 Radial deformation

Radial forces acts differently on inner and outer winding. Axial leakage field will produce radial force on outer winding which will acts outwards tending to stretch the winding produces tensile stress which is also called as hoop stress. Axial leakage field will produce radial force on inner winding which will acts inwards tending to collapse or crush the winding produces compressive stress. Let us consider an outer winding, which is subjected to hoop stresses. The value of the leakage field increases from zero at the outside diameter to a maximum at the inside diameter (at the gap between the two windings). The peak value of flux density in the gap is

$$\mathrm{B_{gp}} = \frac{\sqrt{2}\mathrm{NI}\mu_0}{\mathrm{H_w}} \tag{2.5}$$

The whole winding is in the average value of flux density of half the gap value. The total radial force acting on the winding having a mean diameter of *Dm* (in meters) is given as

$$F_X = \frac{\mu_0 N I^2}{H_w} \times \pi \mathrm{D_m} \tag{2.6}$$

For the outer winding, the conductors close to gap (at the inside diameter) experience higher forces as compared to those near the outside diameter (force reduces linearly from a maximum value at the gap to zero at the outside diameter).

2.4 Effects of deformation

Reduces short circuit withstand capacity

Change in parameters will occurs

Rupture the insulation

Axial deformation failure mode

Tilting of conductor

Axial bending of conductor between spacers

Completely displacement of the winding

Overlap of conductors axially

Radial deformation failure mode

Forced mode Buckling

Free mode buckling

Stretching of outer windings and spiraling of end turns in helical windings

Fig 2.3 Deformed transformer winding

2.5 Transformer modeling in Finite Element Method (FEM)

In FEM modeling complex geometry is subdivided into simpler small parts i.e. finite elements. These finite elements are of triangular shape or tetrahedral shape in which flux density is considered as constant hence magnetic vector potential will vary linearly in each finite element.

Table 2.1 Design specifications for transformer [22]

Winding	Inner Radius (mm)	Outer Radius (mm)	Height (mm)	Turns	Rated Current (A)
LV Winding	306.5	388	1136	200	2100
HV Winding	413	510.5	1136	1200	350

A 40 MVA, 66/11 kV transformer is designed with specifications as given in above Table 2.and the coordinates for designing this transformer is given in Table 2.6. Using data of Table 2.1 and coordinates for designing Table 2.2.a transformer model is designed in Magnet software which is FEM based which is shown in Fig 2.7.For designing this transformer model materials are used as follows copper for winding, silicon steel for core and whole model s enclosed within air box which is taken as boundary. In normal or healthy transformer condition where both the windings are in identical symmetry, rated current will flow through both the windings i.e. primary winding and secondary winding During short circuit condition due to high current large electromagnetic force will produce which will make winding asymmetrical. If windings are asymmetrical and short circuit occurs large force will produce which leads to unequal thrust which acts mostly on ends of the winding and winding will get more deform. winding During short circuit condition due to high current large electromagnetic force will produce which will make winding asymmetrical. If windings are asymmetrical and short circuit occurs large force will produce which leads to unequal thrust which acts mostly on ends of the winding and winding will get more deform.

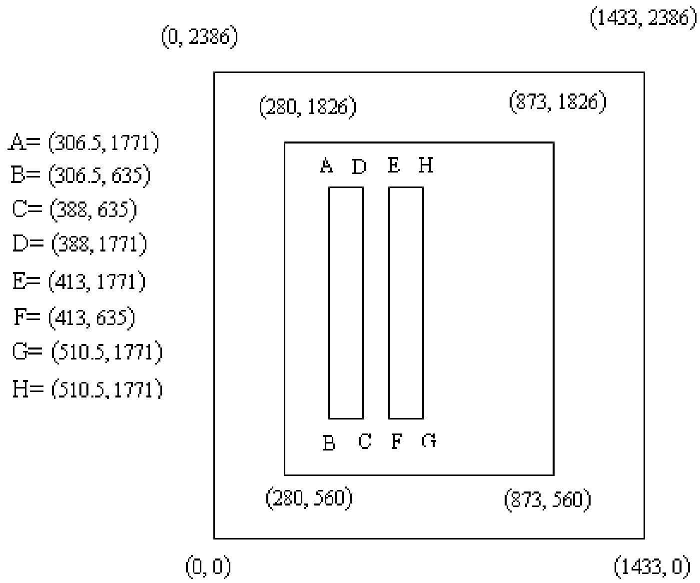

Fig.2.4 Coordinates for transformer design

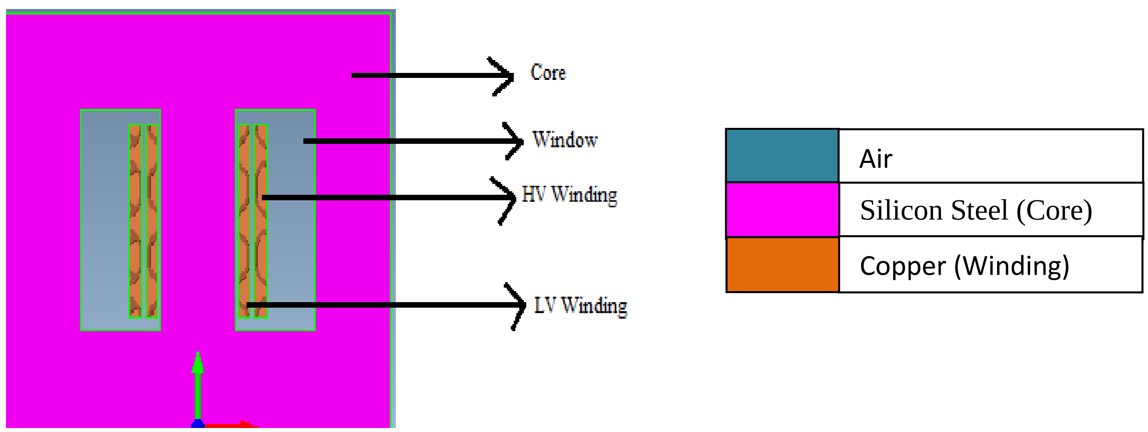

Fig. 2.5 FEM transformer model in Magnet software

In normal condition rated current follows through LV winding and HV winding are

$$\mathrm{I}_{hv} = \frac{P\times10^6}{\sqrt{3}\times V_l} = \frac{40\times10^6}{\sqrt{3}\times66\times10^3} = 349.90 \text{ A} \tag{2.7}$$

$$\mathrm{I}_{lv} = \frac{P\times10^6}{\sqrt{3}\times V_l} = \frac{40\times10^6}{\sqrt{3}\times11\times10^3} = 2099.45 \text{ A)} \tag{2.8}$$

2.5.1 Observation of Axial Deformation through FEM modeling in MAGNET

For observation of axial deformation in transformer two type of deformation are created. First one in which one of the winding i.e. LV winding is reduced by 1% of its height while HV winding kept as same as original height. In second case LV winding shifted axially upward by 1% of its height. These two models are designed in FEM based MAGNET software. If asymmetries are present in transformer e.g. geometric centers are not matching then during short circuit event heavy current (about 5 to 8 times of rated current) will flow which will produce large amount of force which will deform winding more. That's why manufacturer pays special attention to maintain symmetry in windings. In FEM modeling magnetic flux distribution and forces on winding can easily be calculated.

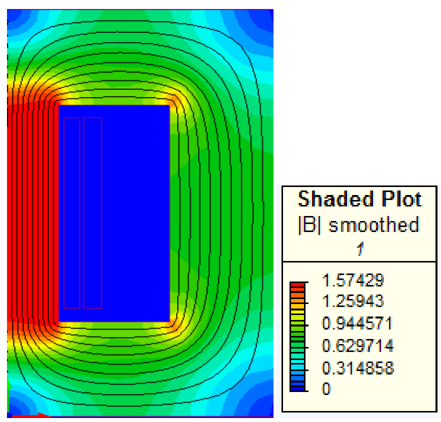

Fig 2.6 Magnetic flux density of healthy coil

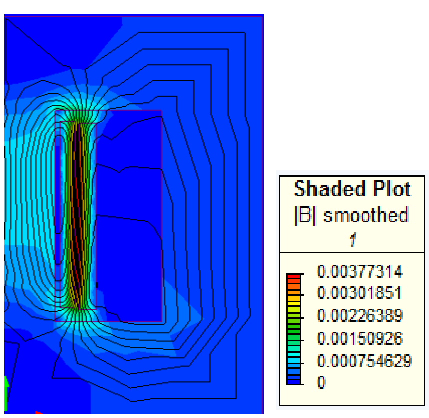

Fig.2.7 Magnetic flux density of 1%axial shift coil

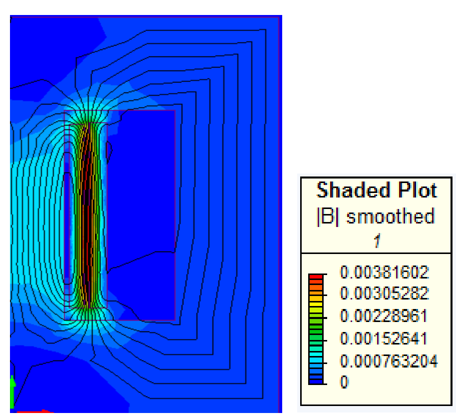

Fig. 2.8 Magnetic flux density 1% axial deformed coil

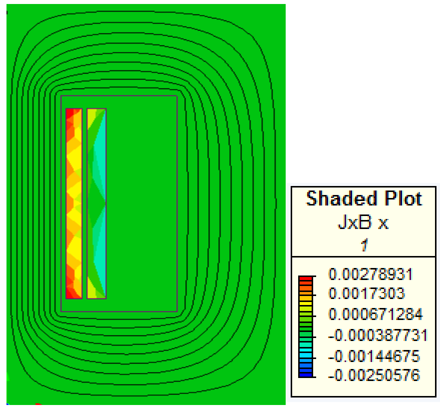

Fig 2.9 Axial force for Normal coil

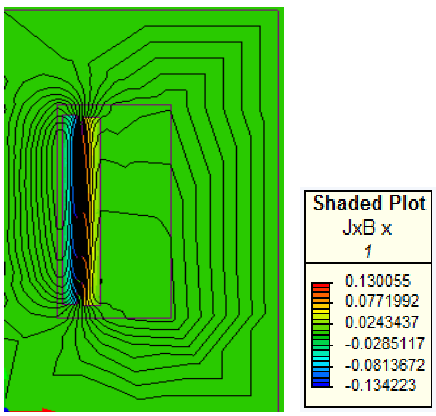

Fig.2.10 Axial force for 1% axial shift coil

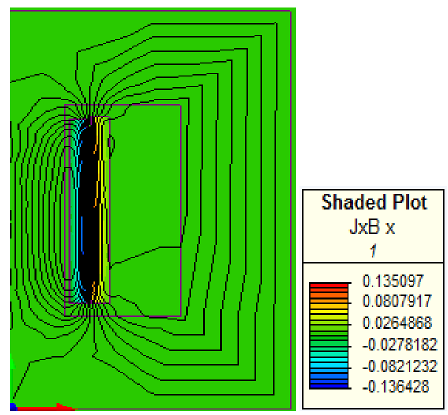

Fig. 2.11 Axial force for 1% axial deformed coil

Table 2.2 Comparison of force generated in transformer with and without deformation (N)

Element	Without Deformation	1% Axial Deformation	1% Axial Shift
LV Winding	149.07	5868.38	5842.93
HV Winding	12.035	5949.2	5921.25

Table 2.2 shows forces generated during normal condition and deformed condition. Forces generated during short circuit in asymmetrical condition are much more compared to normal condition. This leads to further more deformation in winding.

2.6 Conclusion

Short circuit event is main cause for deformation. Electromagnetic forces generated during short circuit will deform coil axially and radialy. Axially and radialy deformed coils have its different failure modes. Forces generated during short circuit are large as compared to forces generated during normal condition. Symmetry should be maintain during manufacturing of transformer otherwise transformer will get more deformed during short circuit events if any asymmetry is present in design.

Chapter 3

Modeling of Power Transformer in High Frequency

3.1 Introduction

Deformations are caused due to force exerted on winding. In power transformer winding core tank forms a complex internal network of resistance ,capacitance and inductance i.e. Series resistance between adjacent sections of coil, resistance between section and ground, capacitance between section and ground, self inductance and mutual inductance. As winding displace, parameter associated with winding will change. Complex internal structure will change. A single layer helical coil has been taken as test coil. Coil is divided into 10 sections. 5 consecutive sections are deformed axially and radialy to get the values of self inductance, mutual inductance and capacitance for healthy coil, axially deformed coil and radialy deformed coil. Change in parameter values can be calculated analytically with Grover's formula and also with MAGNET and ELECTNET software accurately. Changed parameter values are compared with healthy coil parameter to carry out sweep frequency response analysis where deformed coil and healthy (reference) coil parameter plot will be compared.

3.2 Coil under test

A single layer helical 48 inch coil with 1794 turns has been taken for simulation. It consists of copper wire with diameter as 0.0226 inch surrounded by enamel insulation with 0.00205 inch. Coil is tightly wounded on air core with 23 inch diameter. Coil is shielded by inner shield and outer shield. Diameter of Inner shield is 22.6875 inch and diameter of outer shield is 25 inch respectively.

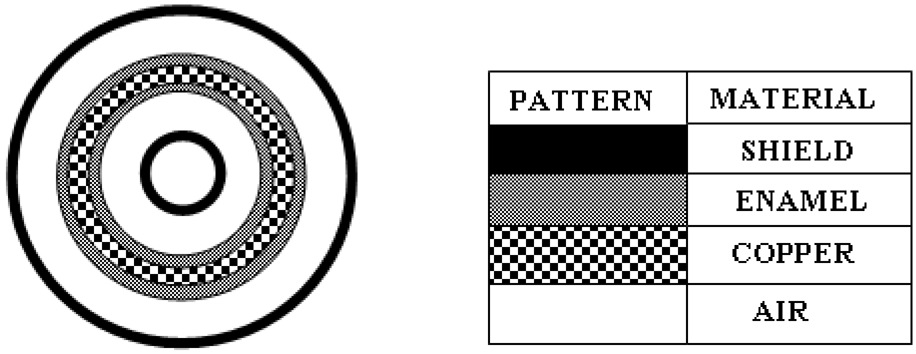

Fig 3.1 Cross sectional view of coil

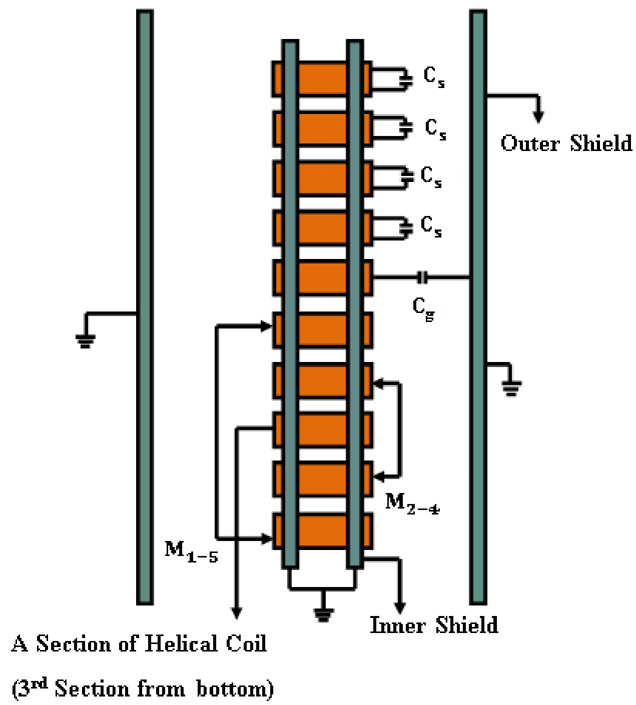

Fig.3.2 Representation of coil physically

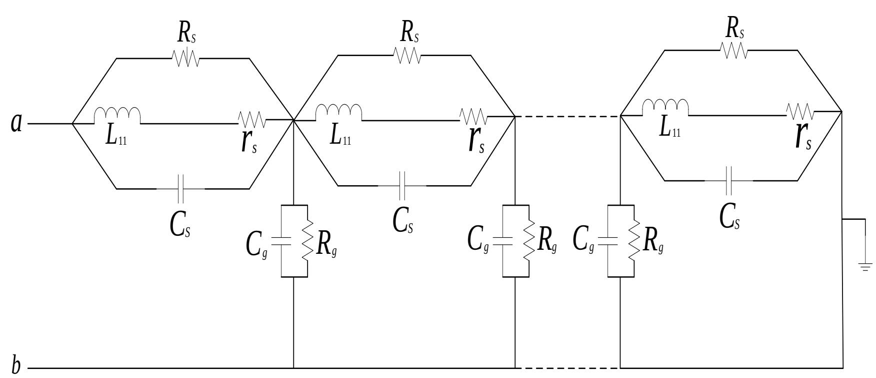

Fig 3.3 Equivalent circuit of coil

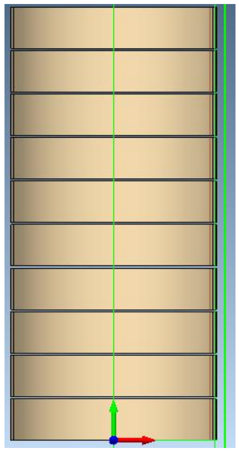

Fig 3.4 Healthy coil model healthy coil

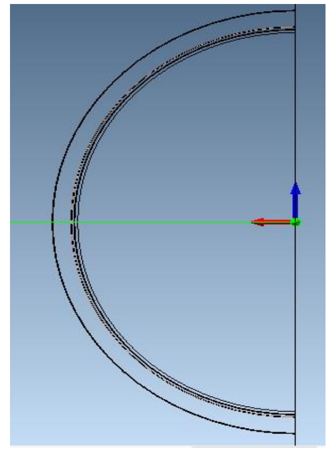

Fig 3.5 Cross section of healthy coil

3.2.1 Axial deformation

This test coil is divided into 10 sections and each section is deformed axially from 1% to 7% of its height. At one time only one section is deformed, while other sections are kept in normal measurement. Excitation is given to only 1st coil while all other coils are unexcited. For 1% of deformation, 1% of coil section is displaced axially like this deformation is made from 1% to 7% for 5 consecutive section of coil. Ground capacitance, self inductance and mutual inductance will change with axial deformation.

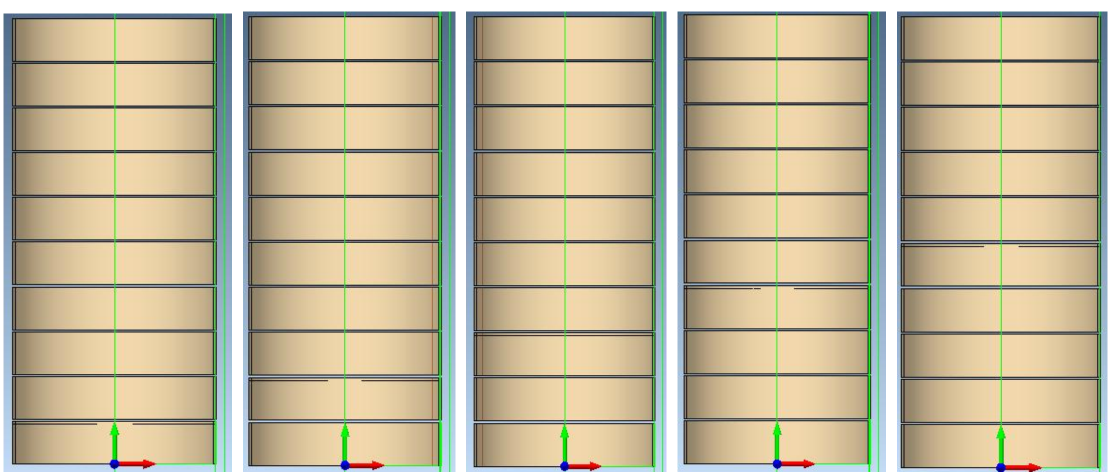

Fig 3.6 Modeling of 5 consecutive axially deformed coil in MAGNET software

3.2.2 Radial deformation

This test coil is divided into 10 sections and each section is deformed radialy from 1% to 7% of its radius. At one time only one section is deformed, while other sections are kept in normal measurement. Excitation is given to only 1st coil while all other coils are unexcited. For 1% of deformation, coil section will displace radialy by 1% like this deformation is made from 1% to 7% for 5 consecutive section of coil. Ground capacitance, self inductance and mutual inductance will change with axial deformation.

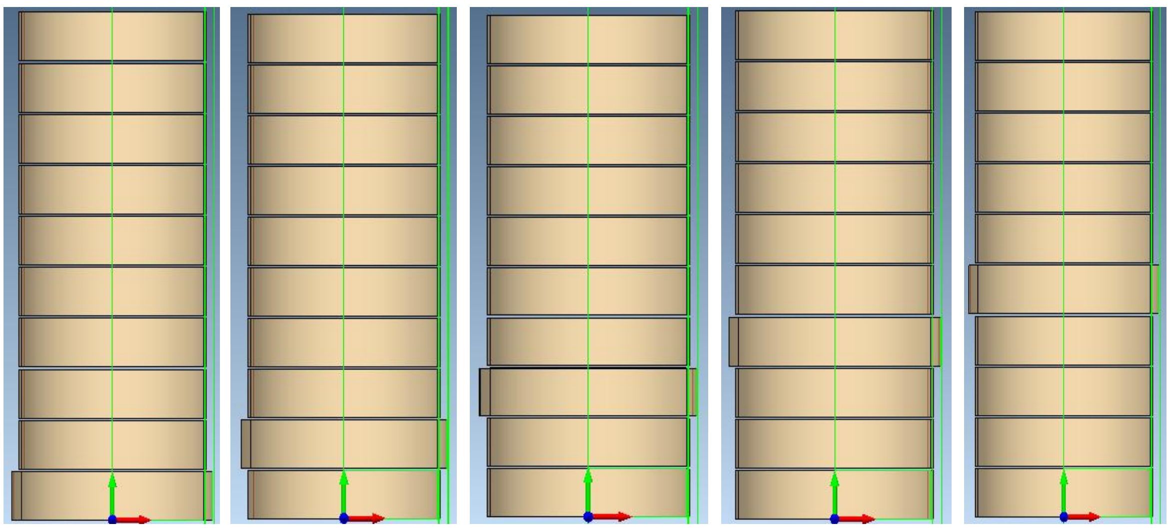

Fig 3.7 Modeling of 5 consecutive radialy deformed coil in MAGNET software

3.3 Calculation of change in parameter

3.3.1 Inductance calculation

3.3.1.1 Grover's formula

Grover's formula is to calculate mutual inductance of coaxial coils. Deformed coil will be displaced but it will be coaxial. Mutual inductance with desired case and with accuracy can be found with this formula. This formula is combination of four integral x_1 , x_2 , x_3 and x_4. Each integral depend on axial distance two coil. Table is also provided with this formula to find out exact value of B_n

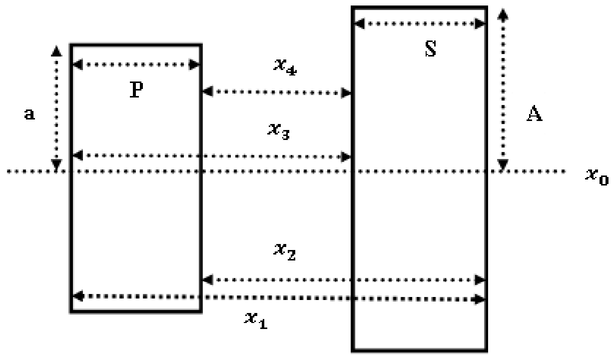

Fig 3.8 Reference diagram for Grover's formula

$$x_1 = x_0 + \frac{P+S}{2} \tag{3.1}$$

$$x_2 = x_0 + \frac{P-S}{2} \tag{3.2}$$

$$x_3 = x_0 - (\frac{P-S}{2}) \tag{3.3}$$

$$x_4 = x_0 - (\frac{P+S}{2}) \tag{3.4}$$

$$M = \frac{2\,\pi^2 a^2 n1n2}{10^9}[r_1B_1 - r_2B_2 - r_3B_3 + r_4B]_4 \tag{3.5}$$

3.3.1.2 Modeling coil in MAGNET software

Values of self and mutual inductance can found out accurately with MAGNET software. Coil with given measurement is designed. Only 1st coil is excited with 1A while all others are unexcited. After simulation values of flux linkage will display with that the values of self and mutual inductances can be found out easily.

$$L_{11} = \frac{\lambda_{11}}{i_1} \tag{3.6}$$

$$M_{1-2} = \frac{\lambda_{12}}{i_1} \tag{3.7}$$

3.3.2 Capacitance calculation

3.3.2.1 Modeling coil in ELECTNET software

Ground capacitance calculation

Values of series and ground capacitance can found out accurately with ELECTNET software. Coil with given measurement is designed. Only 1st electrode is excited with 1V while all others electrodes are unexcited. After simulation values of charges for all electrodes will display with that the values of charges ground capacitance can be found out easily.

$$C = \frac{Q}{V} \tag{3.8}$$

3.4 Parameter calculation

3.4. 1 Healthy coil parameters

Table 3.1 Self inductance and mutual inductances (mH) for healthy coil

L_{11}	M_{1-2}	M_{1-3}	M_{1-4}	M_{1-5}	M_{1-6}	M_{1-7}	M_{1-8}	M_{1-9}	M_{1-10}
28.9495	12.8634	5.7295	3.0131	1.7132	1.0315	0.6493	0.4226	0.2819	0.1919

Table 3.2 Ground capacitance (nF) for healthy coil

C_{g1}	C_{g2}	C_{g3}	C_{g4}	C_{g5}	C_{g6}	C_{g7}	C_{g8}	C_{g9}	C_{g10}
0.766	0.773	0.774	0.771	0.758	0.776	0.767	0.765	0.769	0.762

3.4.2 Deformed coil parameters

3.4.2 .1 Changed in parameter due to axial deformation

1. First section axially deformed

First section axially deformed from 1% to 7% of its height. Values of self and mutual inductance are calculates by designing deformed coil in magnet software.

Table 3.3 Self inductance and mutual inductances (mH) for axially deformed first section

	1%	2%	3%	4%	5%	6%	7%
L_{11}	28.6672	28.3873	28.0994	27.8071	27.5091	27.2096	26.907
M_{1-2}	12.8717	12.8821	12.8914	12.9003	12.9056	12.9145	12.9258
M_{1-3}	5.7309	5.73493	5.73762	5.73919	5.74007	5.74279	5.74702

M_{1-4}	3.01307	3.01533	3.016	3.01744	3.01802	3.01933	3.0206
M_{1-5}	1.71294	1.71426	1.71486	1.71527	1.71646	1.71707	1.71709
M_{1-6}	1.03122	1.03218	1.03258	1.03323	1.03519	1.03553	1.03392
M_{1-7}	0.64945	0.65013	0.65016	0.65057	0.65254	0.65276	0.65088
M_{1-8}	0.4231	0.42275	0.42298	0.42291	0.42374	0.42386	0.42331
M_{1-9}	0.28267	0.28177	0.2823	0.28177	0.28187	0.28193	0.28235
M_{1-10}	0.19287	0.19138	0.192	0.1914	0.19124	0.19129	0.19196

2. Second section axially deformed

Second section axially deformed from 1% to 7% of its height. Values of self and mutual inductance are calculates by designing deformed coil in magnet software.

Table 3.4 Self inductance and mutual inductances (mH) for axially deformed Second section

	1%	2%	3%	4%	5%	6%	7%
L_{11}	28.94296	28.9482	28.9478	28.94781	28.9477	28.9479	28.9478
M_{1-2}	12.76613	12.6677	12.5702	12.47061	12.3703	12.2696	12.1679
M_{1-3}	5.729520	5.72928	5.72979	5.7300502	5.72976	5.73015	5.73014
M_{1-4}	3.012734	3.01262	3.0129	3.0128597	3.01299	3.01281	3.01283
M_{1-5}	1.712417	1.71288	1.71308	1.7130408	1.71303	1.71312	1.71313
M_{1-6}	1.031214	1.03126	1.03104	1.0311084	1.03104	1.03098	1.03092
M_{1-7}	0.649355	0.64923	0.64899	0.6490364	0.64902	0.64914	0.64921
M_{1-8}	0.422777	0.42233	0.42246	0.4224526	0.42247	0.42252	0.42255
M_{1-9}	0.282268	0.28181	0.28226	0.2821642	0.28225	0.28221	0.28216
M_{1-10}	0.192541	0.19185	0.19224	0.1921175	0.19228	0.19209	0.19199

3. Third section axially deformed

Third section axially deformed from 1% to 7% of its height. Values of self and mutual inductance are calculates by designing deformed coil in magnet software

Table 3.5 Self inductance and mutual inductances (mH) for axially deformed Third section

	1%	2%	3%	4%	5%	6%	7%
L_{11}	28.94621	28.94784	28.94814	28.94816	28.94772	28.94817	28.94782

M_{1-2}	12.8638	12.86414	12.86291	12.8631	12.86415	12.86321	12.86399
M_{1-3}	5.681479	5.633674	5.584802	5.536257	5.487991	5.437979	5.389212
M_{1-4}	3.012304	3.013273	3.012686	3.012635	3.013157	3.012715	3.013047
M_{1-5}	1.712719	1.712832	1.712587	1.713094	1.712995	1.712988	1.713126
M_{1-6}	1.030628	1.031244	1.030895	1.031048	1.030981	1.031078	1.030889
M_{1-7}	0.648755	0.649299	0.649081	0.649288	0.649172	0.649212	0.649035
M_{1-8}	0.422816	0.422284	0.422472	0.422459	0.422443	0.422382	0.422444
M_{1-9}	0.282757	0.28165	0.282091	0.281984	0.282051	0.281976	0.282193
M_{1-10}	0.19315	0.19161	0.19214	0.191919	0.191928	0.192029	0.192104

4. Fourth section axially deformed

Fourth section axially deformed from 1% to 7% of its height. Values of self and mutual inductance are calculates by designing deformed coil in magnet software.

Table 3.6 Self inductance and mutual inductances (mH) for axially deformed fourth section

	1%	2%	3%	4%	5%	6%	7%
L_{11}	28.9447	28.9447	28.9482	28.9487	28.9478	28.9481	28.9487
M_{1-2}	12.8626	12.8626	12.863	12.8633	12.8641	12.8629	12.8634
M_{1-3}	5.72859	5.72858	5.72909	5.72933	5.72982	5.72907	5.72935
M_{1-4}	2.98585	2.95972	2.93343	2.90694	2.88065	2.85341	2.82638
M_{1-5}	1.7123	1.71236	1.71314	1.71291	1.71319	1.71298	1.71278
Coil#6	1.03066	1.03072	1.031	1.03066	1.03087	1.0312	1.03071
M_{1-7}	0.64933	0.64908	0.6493	0.64891	0.64902	0.64942	0.64899
M_{1-8}	0.42281	0.42273	0.42249	0.42248	0.42245	0.4224	0.42251
M_{1-9}	0.28211	0.28234	0.28202	0.28224	0.28223	0.28172	0.28219
M_{1-10}	0.19238	0.19279	0.19194	0.19225	0.19214	0.1916	0.19216

5. Fifth section axially deformed

Fifth section axially deformed from 1% to 7% of its height. Values of self and mutual inductance are calculates by designing deformed coil in magnet software.

Table 3.7 Self inductance and mutual inductances (mH) for axially deformed fifth section

	1%	2%	3%	4%	5%	6%	7%
L_{11}	28.9458	28.9482	28.9461	28.9482	28.9482	28.9482	28.9476
M_{1-2}	12.8636	12.863	12.8636	12.863	12.863	12.863	12.8639
M_{1-3}	5.72899	5.72897	5.72912	5.729	5.72895	5.72915	5.72967
M_{1-4}	3.01254	3.01256	3.01245	3.01257	3.01265	3.01257	3.01307
M_{1-5}	1.69684	1.68245	1.66634	1.65147	1.63576	1.62023	1.6046
M_{1-6}	1.03085	1.03091	1.03067	1.03101	1.03113	1.03111	1.03117
M_{1-7}	0.64946	0.64941	0.64887	0.64928	0.64928	0.64925	0.64915
M_{1-8}	0.42279	0.42252	0.42256	0.42248	0.42236	0.42242	0.42247
M_{1-9}	0.28207	0.28198	0.28218	0.28206	0.28184	0.28196	0.2821
M_{1-10}	0.19219	0.19183	0.19251	0.19198	0.19181	0.19191	0.19202

3.4.2.2 Changed in parameter due to radial deformation

1. First section radialy deformed

First section radialy deformed from 1% to 7% of its height. Values of self and mutual inductance are calculates by designing deformed coil in magnet software.

Table 3.8 Self inductance and mutual inductances (mH) for radialy deformed first section

	1%	2%	3%	4%	5%	6%	7%
L_{11}	29.35	29.7513	30.15602	30.5578	30.9626	31.3716	31.7601
M_{1-2}	12.9684	13.0597	13.13565	13.2008	13.2541	13.2967	13.3296
M_{1-3}	5.792913	5.85642	5.917399	5.97845	6.0373	6.09397	6.148
M_{1-4}	3.052342	3.09203	3.13109	3.16972	3.20827	3.24616	3.28243
M_{1-5}	1.738202	1.76338	1.787813	1.81331	1.83825	1.86265	1.88575
M_{1-6}	1.047493	1.06365	1.080179	1.09632	1.11246	1.12878	1.14504
M_{1-7}	0.659902	0.67061	0.681565	0.69223	0.70317	0.71402	0.72498
M_{1-8}	0.429671	0.43699	0.44405	0.45163	0.45902	0.46634	0.47311
M_{1-9}	0.286947	0.29214	0.296467	0.30221	0.30728	0.31219	0.31591
M_{1-10}	0.195439	0.19904	0.201844	0.20606	0.20954	0.21302	0.21511

2. Second section radialy deformed

Second section radialy deformed from 1% to 7% of its height. Values of self and mutual inductance are calculates by designing deformed coil in magnet software.

Table 3.9 Self inductance and mutual inductances (mH) for radialy deformed second section

	1%	2%	3%	4%	5%	6%	7%
L_{11}	28.9478	28.9478	28.9478	28.9486	28.9494	28.9482	28.9491
M_{1-2}	12.9694	13.0597	13.1363	13.1997	13.2537	13.2962	13.3298
M_{1-3}	5.72992	5.72949	5.72967	5.72923	5.72944	5.72906	5.72911
M_{1-4}	3.01295	3.01305	3.01338	3.01253	3.0128	3.01257	3.01287
M_{1-5}	1.71295	1.71262	1.71298	1.71285	1.71287	1.71309	1.71287
M_{1-6}	1.03117	1.0313	1.03125	1.0307	1.03079	1.03099	1.03092
M_{1-7}	0.64914	0.6494	0.64934	0.64885	0.64888	0.64905	0.64894
M_{1-8}	0.42243	0.42238	0.42236	0.42244	0.42243	0.42241	0.42235
M_{1-9}	0.28203	0.28167	0.28171	0.28227	0.28225	0.28214	0.28203
M_{1-10}	0.19196	0.19148	0.19154	0.19228	0.19232	0.19221	0.19204

3. Third section radialy deformed

Third section radialy deformed from 1% to 7% of its height. Values of self and mutual inductance are calculates by designing deformed coil in magnet software.

Table 3.10 Self inductance and mutual inductances (mH) for radialy deformed third section

	1%	2%	3%	4%	5%	6%	7%
L_{11}	28.9476	28.9478	28.9476	28.9478	28.9475	28.9486	28.948
M_{1-2}	12.864	12.8627	12.8642	12.8641	12.864	12.8631	12.8629
M_{1-3}	5.79366	5.85581	5.91812	5.97801	6.0369	6.09365	6.14732
M_{1-4}	3.01321	3.01251	3.01299	3.01321	3.01319	3.01277	3.0125
M_{1-5}	1.71298	1.71323	1.7131	1.71288	1.71289	1.71318	1.71302
M_{1-6}	1.03129	1.03111	1.03101	1.03145	1.03124	1.03166	1.03114
M_{1-7}	0.64914	0.64955	0.64888	0.64919	0.64934	0.64954	0.64935
M_{1-8}	0.42241	0.42257	0.4224	0.42226	0.42243	0.42241	0.42255
M_{1-9}	0.282	0.28195	0.28226	0.28161	0.28182	0.28172	0.28207

M_{1-10}	0.19197	0.19187	0.19224	0.19153	0.19168	0.19167	0.19201

4. Fourth section radialy deformed

Fourth section radialy deformed from 1% to 7% of its height. Values of self and mutual inductance are calculates by designing deformed coil in magnet software.

Table 3.11 Self and mutual inductances (mH) for radialy deformed fourth section

	1%	2%	3%	4%	5%	6%	7%
L_{11}	28.9479	28.9486	28.9481	28.9473	28.9477	28.9476	28.94491
M_{1-2}	12.8628	12.8632	12.863	12.8636	12.8625	12.8625	12.86326
M_{1-3}	5.72874	5.72894	5.72872	5.72945	5.72915	5.72876	5.728875
M_{1-4}	3.05241	3.0918	3.13067	3.16983	3.20801	3.24592	3.281906
M_{1-5}	1.71312	1.71325	1.71299	1.71332	1.71271	1.71332	1.712304
M_{1-6}	1.03147	1.03148	1.03105	1.0316	1.03151	1.03143	1.031107
M_{1-7}	0.64956	0.64957	0.64913	0.64962	0.64939	0.64954	0.649412
M_{1-8}	0.42247	0.42249	0.42242	0.42269	0.4224	0.42272	0.422637
M_{1-9}	0.28181	0.28182	0.28202	0.28216	0.2817	0.28228	0.281926
M_{1-10}	0.19171	0.19172	0.19198	0.19195	0.19162	0.1922	0.192069

5. Fifth section radialy deformed

Fifth section radialy deformed from 1% to 7% of its height. Values of self and mutual inductance are calculates by designing deformed coil in magnet software

Table 3.12 Self inductance and mutual inductances (mH) for radialy deformed fifth section

	1%	2%	3%	4%	5%	6%	7%
L_{11}	28.9477	28.9483	28.9477	28.9474	28.9486	28.9477	28.9477
M_{1-2}	12.8641	12.8631	12.8641	12.8637	12.8632	12.8641	12.8641
M_{1-3}	5.72984	5.72891	5.72972	5.72968	5.72881	5.72979	5.72981
M_{1-4}	3.01292	3.01255	3.013	3.01295	3.01282	3.013	3.013
M_{1-5}	1.7383	1.76332	1.78833	1.81369	1.83848	1.86307	1.88663
M_{1-6}	1.03093	1.03108	1.03108	1.03129	1.03178	1.03099	1.03106
M_{1-7}	0.64892	0.64921	0.64901	0.64928	0.64977	0.64889	0.64901

M_{1-8}	0.42241	0.42245	0.42233	0.42245	0.42231	0.42239	0.42237
M_{1-9}	0.28221	0.28204	0.28197	0.28207	0.28128	0.28217	0.28206
M_{1-10}	0.19216	0.19199	0.19187	0.19197	0.19115	0.19216	0.19199

6. Axial overlapping of conductor

In 1st section of coil one half of the number of turns of coil overlaps over other half of number of turns keeping other sections same.

Table 3.13 Self inductance and mutual inductances (mH) for axially deformed first section

L_{11}	M_{1-2}	M_{1-3}	M_{1-4}	M_{1-5}	M_{1-6}	M_{1-7}	M_{1-8}	M_{1-9}	M_{1-10}
36.7459	14.1234	6.7899	3.6645	2.1207	1.2938	0.8231	0.5399	0.3629	0.2482

3.5 Conclusion

Disturbance in mechanical integrity of transformer will affect electrical response of the winding. By modeling helical coil in MAGNET and ELECTNET software changed in parameter are calculated by deforming coil axially and radialy.

Chapter 4

Sweep Frequency Response Analysis

4.1 Methods to detect deformation

1. Reactance Comparison Method

In this method reactance of winding is measured before the short circuit test and after the short circuit test. These two reactance are compared and deformation is check based on that. As per IEC -60075 standards, reactance value should not exceed 1% for transformer with 100MVA rating and above. Because of low sensitivity of this method it is not performed on transformers which are already in service.

2. Frequency Response Analysis

This method is powerful tool to diagnose deformation in winding. In FRA method transfer functions is observed over wide frequency range starting from Few Hz to MHz Under this analysis two methods there i.e. Low Impulse Voltage (LVI) and Sweep Frequency Response Analysis (SFRA).In LVI method at low voltage impulse is injected across transformer terminals. Transfer function is derived from the LVI method response.LVI has limitation its sensitivity is restricted to frequency range from 10 kHz to 1MHz.Due to frequency restriction detection of deformation in winding becomes difficult.

In SFRA method frequency sweep is done on sinusoidal signal. Sweep Frequency Response Analysis is graphical comparative method in which reference signature of transformer is compared with measured response. From previous chapter it is known parameter self inductance, mutual inductance and capacitance changes due to deformation. These deformed parameters and healthy coil parameter are used in matlab code to generate healthy plot and deformed plot of transformer. Two graphs are compares to check the deformation in measured response. Likewise SFRA for axial and radial deformed coils have been observed. If reference fingerprint is not available then sister unit fingerprint can be consider as reference fingerprint and deviation can be observed.

4.2 SFRA is better

SFRA is better compared to other method as

1. It consume less time
2. Economical as less number of equipment are needed
3. Deformation can be observed without opening the power transformer
4. Better signal to noise ratio
5. More sensitivity
6. Better resolution
7. Frequency range is wide

4.3 Result

Changed parameters obtained by deforming coil in MATLAB and ELECTNET software are used in matlab coding to get graphs of input current Vs frequency, resistance Vs frequency, reactance Vs frequency. Each graphs shows change in parameter with respect to frequency from 1% to 7% of axial deformation for 1st section of coil. Healthy coil graph is reference and all other are measured responses.Deformation are observed clearly by visual inspection.More the measured response deviates from healthy coil graph represents more deviation and vice versa

Coil get more deform in radial deformation than axial deformation. Change in Parameter value is more in radial deformation than axial deformation.

4.3.1 Radial defomation

Input current Vs Frequency

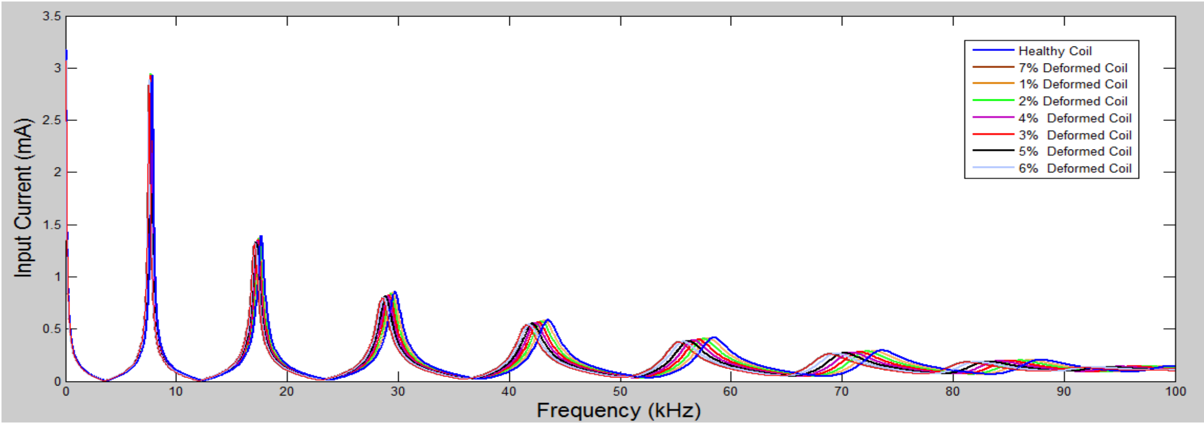

Fig 4.1 Input current Vs Frequency graph for healthy and deformed coil

Resistance Vs Frequency

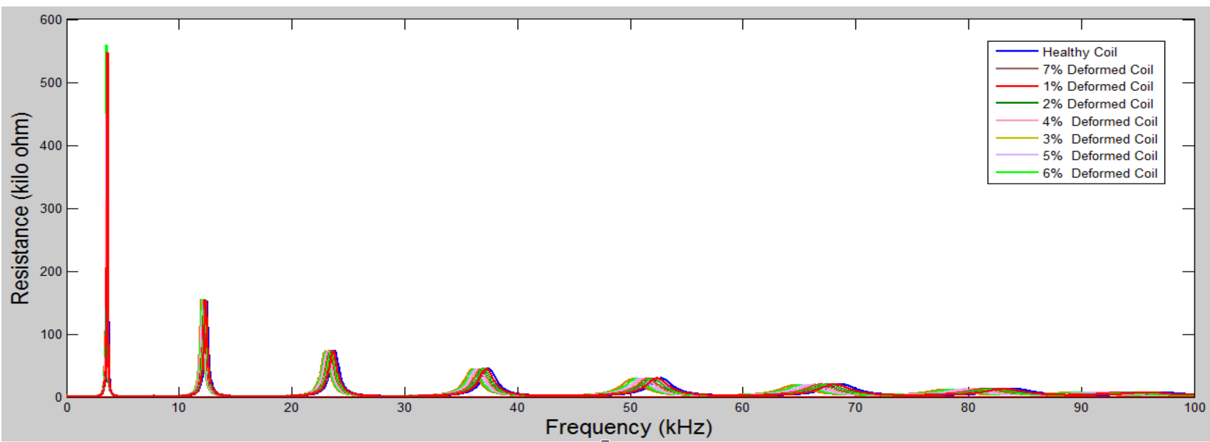

Fig 4.2 Resistance Vs Frequency graph for healthy and deformed coil

Reactance Vs Frequency

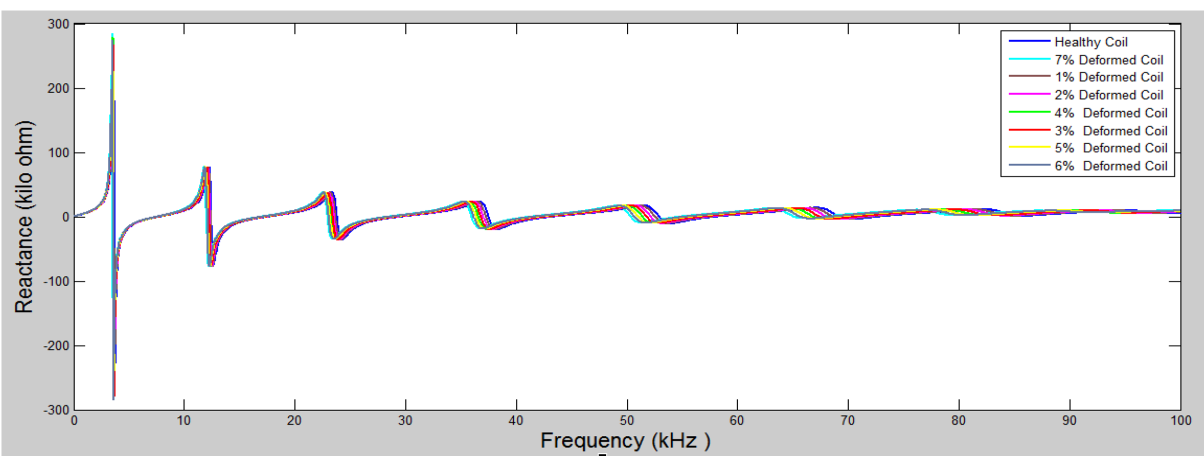

Fig 4.3 Reactance Vs Frequency graph for healthy and deformed coil

4.3.2 Axial deformation

Input current Vs Frequency

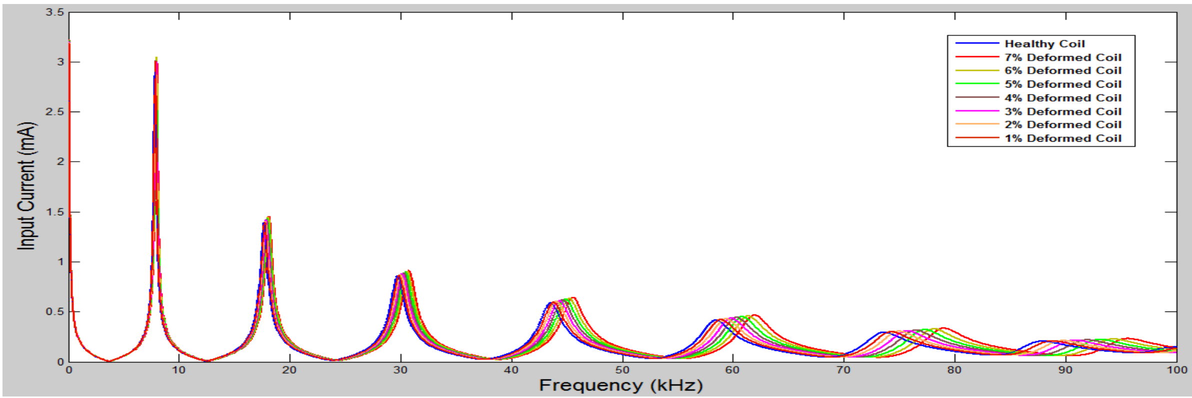

Fig 4.4 Input current Vs Frequency graph for healthy and deformed coil

Resistance Vs Frequency

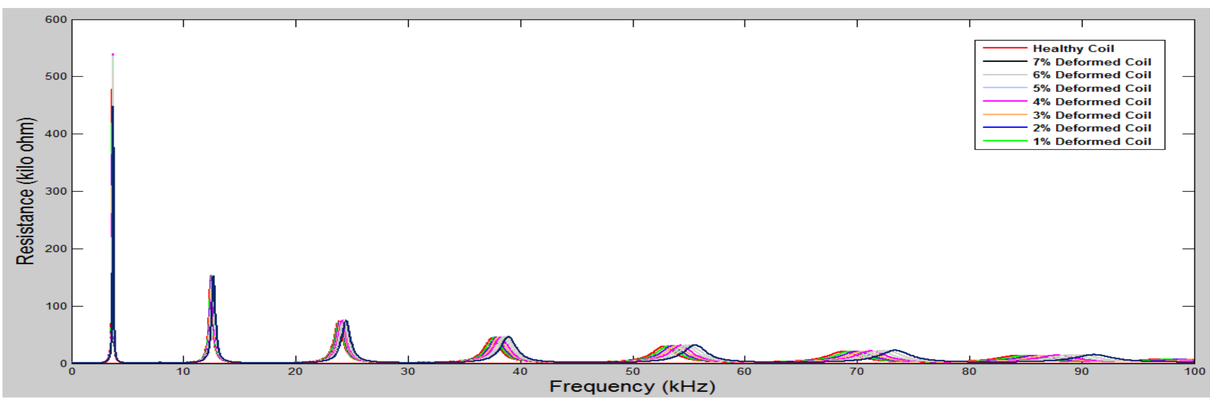

Fig 4.5 Resistance Vs Frequency graph for healthy and deformed coil

Reactance Vs Frequency

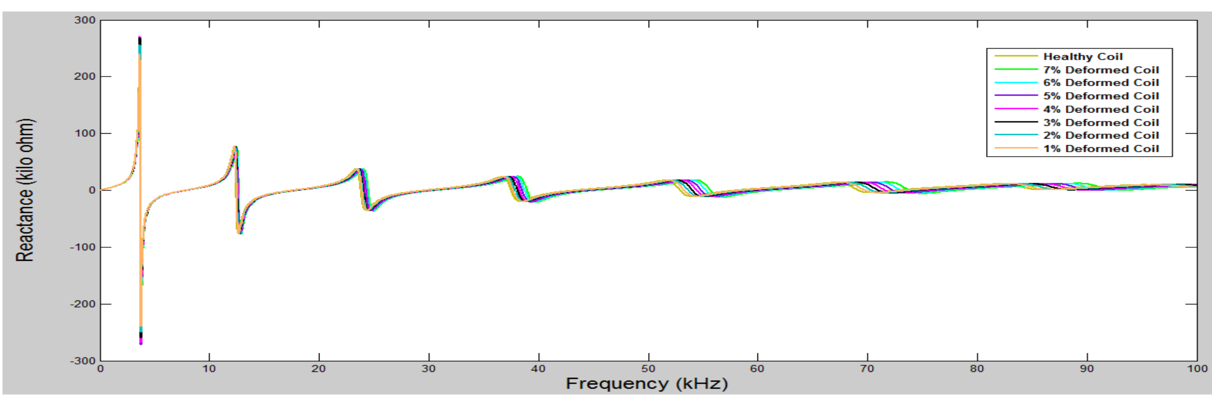

Fig 4.6 Reactance Vs Frequency graph for healthy and deformed coil

4.4 Experimental Study

4 .4.1 Introduction

SFRA test is conducted on 500kVA ,11kV/440v transformer to generate reference signature of transformer. Every transformer has its unique signature. In this experiment input voltage is given to one end of transformer winging and output voltage is measured cross other end of the winding. Input voltage and output voltage re measured with varying frequency from 10Hz to 9Mz. Likewise test is performed for R,Y and B winding. Voltage gain (Vout/Vin) in db is being plotted on semi log graph which represents reference signature of transformer.

4.4.2 Apparatus Required

Transformer 500Kva, 11kV/400V

Resistor 2 (10ohm)

Digital Storage Oscilloscope

Function Generator

4.4.3 Measurement Circuit

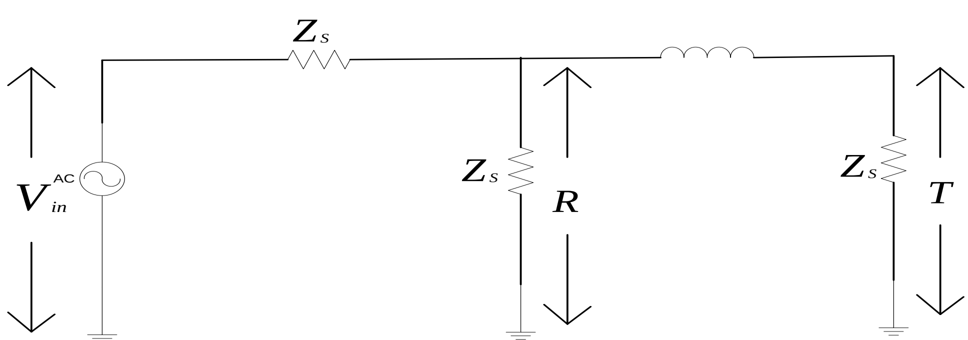

Fig 4.7 Measurement diagram for SFRA test

Fig. 4.8 Experimental setup

4.4.4 Result

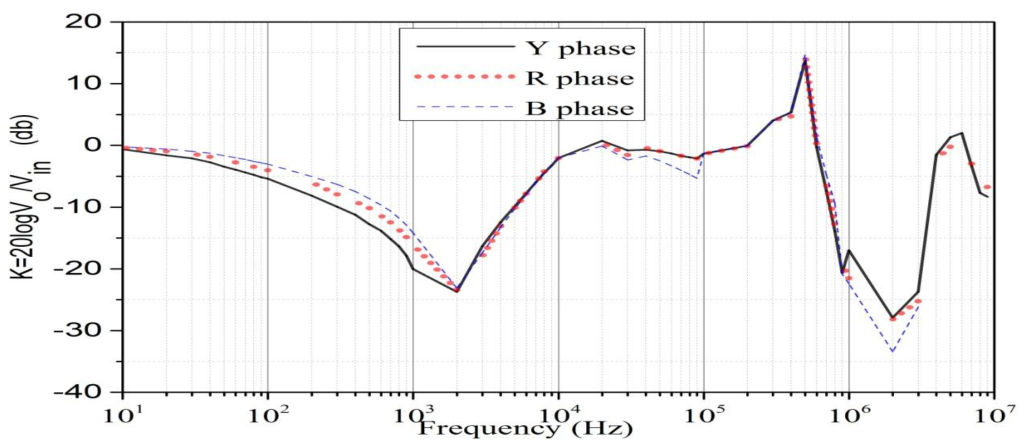

Fig 4.9 Frequency Vs K (Voltage Gain)

In sweep frequency response analysis two plots are needed for comparison i.e. reference plot is compared with deformed plot. Practically deforming coil in lab is difficult due to lab limitations. In this experiment of SFRA method, reference graph of R phase, Y phase, B phase are obtained. To obtain deformation we have to manually make deformation in winding using hammer or other means. This kind of damage to transformer we can't afford in lab. To create formation in winding experiment is carried out BHEL and other research labs.

4.5 Conclusion

SFRA is powerful tool to detect deformation in winding. Extent of deformation can be calculated by observing deviation of measured response from reference response.

Chapter 5

Numerical Techniques

5.1 Introduction

SFRA is graphical method to check deformation. It need trained person to observe deviation clearly. The conclusion whether the coil is deformed or not totally depends on the skill and experience of person. Sometime small deviations in graphs are not easily visible. Chances of wrong conclusion are more in slightly deformed winding. To avoid such confusion and make SFRA easier to understand numerical techniques are needed. Deviations are shown in numerical values in this method thus an inexperienced person can also detect deviation in winding.

5.2 Numerical Techniques

Cross correlation

Standard deviation

Absolute sum of logarithmic error

Absolute difference

Mean square error

Min max ratio

Comparative standard deviation

5.2.1 Cross Correlation Coefficient

Cross-correlation takes two sets of numbers and checks linear association of variables. CCC varies from +1 to -1.CCC value +1 indicates strong correlation between two set, 0 indicates no linear association and values in between 0 and +1 indicates more or less deformed depend on the deviation between two sets.

$$\mathrm{CCC}_{(X,Y)} = \frac{\sum_{i=1}^{N} X(i)Y(i)}{\sqrt{\sum_{i=1}^{N}[X(i)-\bar{X}]^2 \times \sum_{i=1}^{N}[Y(i)-\bar{Y}]^2}}$$

5.2.2 Standard Deviation

Standard deviation measures the amount of variation or dispersion in two data sets standard deviation value as 0 indicated perfect match of two sets. SD 0 indicates close to 0 indicates data points are near to the mean of the set, while SD between 0 to 1 indicates that the data points are spread out over a wider range of values.

$$\mathrm{SD}_{(X,Y)} = \sqrt{\frac{\sum_{i=1}^{N}[Y(i)-X(i)]^2}{N-1}}$$

5.2.3 Absolute sum of Logarithmic Error

ASLE value as 0 indicates perfect matching, values other than 0 indicates deviation.

$$\mathrm{ASLE}_{(X,Y)} = \frac{\sum_{i=1}^{N}\sum_{i=1}^{N}|20\log_{10} Y(i) - 20\log_{10} X(i)|}{N}$$

5.2.4 Mean Square Error

The unique quality of MSE is that it suppresses small errors and magnifies large errors. MSE value 0 indicates two sets match perfectly. Other than 0 all values indicates deviation.

$$\mathrm{MSE}_{(X,Y)} = \frac{\sum_{i=1}^{N}(X(i)-Y(i))^2}{N}$$

5.2.5 Absolute Difference

This technique is sensitive towards minor difference between two data sets. It is same as ASLE only logarithmic conversion of data has not done. AB value as 0 indicates perfect matching.

$$\mathrm{AD}_{(\mathrm{X,Y})} = \frac{\sum_{i=1}^{N} |Y(i) - X(i)|}{N}$$

5.2.6 Min Max Ratio

This technique is sensitive towards peak changes in magnitude plots. Ideal value for MM is 1. This technique is receptive towards change in resonance shapes which is caused due to small change in amplitude

$$MM_{(X,Y)} = \frac{\sum_{i=1}^{N} \min\,(Y(i), X(i))}{\sum_{i=1}^{N} \max\,(Y(i), X(i))}$$

5.2.7 Comparative Standard Deviation

CSD value as 0 indicates perfectly matching of two sets. Values other than 0 to 1 indicate deviation.

$$CSD_{(X,Y)} = \sqrt{\frac{\sum_{i=1}^{N}[(X(i) - \bar{X}) - (Y(i) - \bar{Y})]^2}{N - 1}}$$

Table 5.1 Perfect match values for statistical parameter

Serial no.	Statistical parameter	Perfect match value (no deviation)
1	cross correlation coefficient	1
2	standard deviation	0
3	Absolute sum of logarithmic error	0
4	Min max ratio	1
5	Mean square error	0
6	Comparative standard deviation	0
7	Absolute difference	0

Values close to perfect match values represent healthy winding and away from perfect match values represent deviation in winding. Numerical techniques make SFRA simpler. Untrained person can also verify the values and observe deviation in graph hence deformation in winding

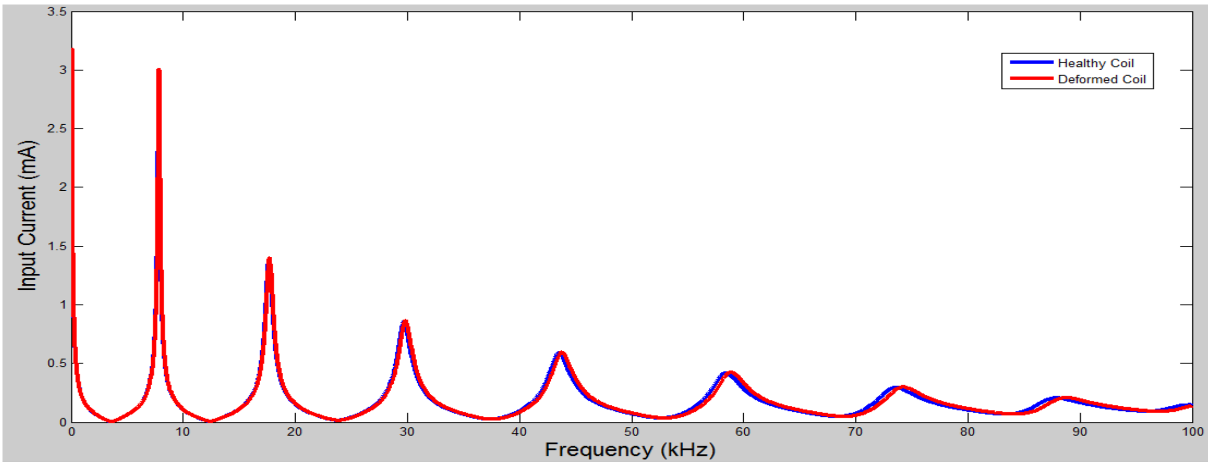

Fig 5.1 Input Current Vs Frequency graph of 1st section with 1% axial deformation

In above fig 5.1 deformed coil is following healthy coils respond very closely. Careful observation is needed to check small deviation in winding. In table 5.2 and table 5.3 values of deviation are measured with numerical techniques are shown. With numerical technique deviation observation becomes more clear and simple.

Table 5.2 Values of numerical technique for 1st section axially deformed

	1%	2%	3%	4%	5%	6%	7%
CCC	0.9932	0.973	0.9408	0.8994	0.8511	0.8	0.7484
CCC1	0.9971	0.9881	0.9731	0.9525	0.9265	0.898	0.8682
CCC2	0.989	0.956	0.9021	0.8311	0.7476	0.6562	0.5606
CCC3	0.9666	0.8756	0.7346	0.5599	0.3764	0.2022	0.0434
CCC4	0.9114	0.7028	0.4687	0.2158	-0.0629	-0.3271	-0.5159
SD	0.0428	0.0977	0.1723	0.2558	0.3399	0.4195	0.4918
SD1	0.028	0.058	0.0896	0.1225	0.1576	0.1928	0.2283
SD2	0.0517	0.0998	0.1476	0.1944	0.24	0.2842	0.3267
SD3	0.0682	0.1598	0.2604	0.3346	0.364	0.3511	0.3028
SD4	0.0741	0.1975	0.3681	0.5296	0.6467	0.7137	0.732
ASLE	0.0021	-0.0098	-0.051	-0.1044	-0.1521	-0.1852	-0.2
ASLE1	0.043	0.0913	0.1444	0.2026	0.2677	0.3363	0.4091

ASLE2	0.0571	0.098	0.1273	0.1437	0.1459	0.1335	0.105
ASLE3	-0.2296	-0.4907	-0.7651	-0.9999	-1.1545	-1.2077	-1.1446
ASLE4	0.1211	0.3406	0.6972	1.0714	1.3493	1.4787	1.4306
MM	0.9074	0.9484	0.7494	0.6856	0.6309	0.5849	0.5459
MM1	0.9536	0.9541	0.864	0.8209	0.7801	0.7444	0.7121
MM2	0.91	0.9651	0.7508	0.6825	0.6215	0.5674	0.5193
MM3	0.8631	0.9635	0.6486	0.5597	0.4879	0.4331	0.3917
MM4	0.8746	0.8943	0.6786	0.6214	0.5773	0.5408	0.5114
MSE	0.0018	0.0016	0.0297	0.0654	0.1155	0.1759	0.2417
MSE1	0.0007	0.0009	0.008	0.015	0.0248	0.0371	0.052
MSE2	0.0027	0.0002	0.0217	0.0377	0.0575	0.0806	0.1065
MSE3	0.0046	0.0009	0.0676	0.1117	0.1322	0.123	0.0915
MSE4	0.0055	0.000001	0.1353	0.2799	0.4174	0.5084	0.5348
CSD	0.0272	0.0195	0.0805	0.1053	0.1286	0.1497	0.1687
CSD1	0.0305	0.0315	0.0925	0.1232	0.1536	0.1813	0.2067
CSD2	0.0283	0.0115	0.0858	0.1134	0.1397	0.1643	0.1873
CSD3	0.0281	0.0092	0.0789	0.102	0.1227	0.1405	0.1557
CSD4	0.0201	0.0175	0.0582	0.072	0.0837	0.0942	0.1035
AD	0.0009	0.0008	0.0039	0.0057	0.0076	0.0094	0.011
AD1	0.0013	0.0014	0.004	0.0055	0.007	0.0086	0.0102
AD2	0.0023	0.0007	0.0066	0.0087	0.0107	0.0127	0.0146
AD3	-0.003	0.0014	-0.0116	-0.0149	-0.0163	-0.0157	-0.0135
AD4	0.0033	0.00005	0.0164	0.0237	0.0289	0.0319	0.0327

Table 5.3 Values of numerical technique for 1st section radialy deformed

	1%	2%	3%	4%	5%	6%	7%
CCC	0.9849	0.9458	0.8923	0.8337	0.7746	0.7182	0.669
CCC1	0.9873	0.9554	0.9132	0.868	0.8231	0.7807	0.7433
CCC2	0.9818	0.9337	0.8637	0.7823	0.6947	0.605	0.5221
CCC3	0.9672	0.8693	0.7173	0.5354	0.3372	0.1366	-0.0421
CCC4	0.8834	0.572	0.1485	-0.2427	-0.527	-0.668	-0.6557
SD	0.0693	0.14	0.2137	0.2868	0.3571	0.4257	0.4915
SD1	0.0587	0.1118	0.1612	0.2072	0.2503	0.2909	0.3273
SD2	0.0578	0.1185	0.1805	0.242	0.3042	0.3672	0.4259
SD3	0.0415	0.0664	0.0777	0.0773	0.067	0.0479	0.0225
SD4	0.0637	0.1163	0.1636	0.2021	0.2272	0.2419	0.2531

ASLE	0.0261	0.057	0.0938	0.1335	0.1703	0.2063	0.2446
ASLE1	-0.0903	-0.1678	-0.2366	-0.2976	-0.3518	-0.4004	-0.4416
ASLE2	-0.0765	-0.1732	-0.2873	-0.4152	-0.5584	-0.7152	-0.8679
ASLE3	0.1843	0.3485	0.4972	0.6246	0.7343	0.8229	0.8797
ASLE4	-0.122	-0.2355	-0.3486	-0.446	-0.5055	-0.5325	-0.5489
MM	0.8872	0.7938	0.7169	0.6568	0.6089	0.572	0.5444
MM1	0.9082	0.832	0.7693	0.7183	0.6736	0.6373	0.6072
MM2	0.8867	0.7923	0.712	0.6455	0.5888	0.54	0.5006
MM3	0.8665	0.7516	0.6564	0.5814	0.5211	0.4729	0.4371
MM4	0.8752	0.7803	0.7088	0.6641	0.6441	0.645	0.6587
MSE	0.0048	0.0196	0.0456	0.0822	0.1274	0.1812	0.2414
MSE1	0.0034	0.0125	0.0259	0.0428	0.0625	0.0845	0.1069
MSE2	0.0033	0.014	0.0325	0.0585	0.0924	0.1346	0.181
MSE3	0.0017	0.0044	0.006	0.006	0.0045	0.0023	0.0005
MSE4	0.0041	0.0135	0.0267	0.0408	0.0515	0.0584	0.0639
CSD	0.0401	0.0754	0.1058	0.1309	0.1517	0.1689	0.1823
CSD1	0.063	0.1175	0.1631	0.2005	0.2312	0.2567	0.2768
CSD2	0.0361	0.0684	0.0976	0.1227	0.1446	0.1637	0.1793
CSD3	0.0274	0.0541	0.0784	0.099	0.1163	0.1306	0.1414
CSD4	0.0198	0.0361	0.0491	0.0578	0.0627	0.0643	0.0629
AD	-0.0015	-0.0031	-0.0048	-0.0064	-0.008	-0.0095	-0.011
AD1	-0.0026	-0.005	-0.0072	-0.0093	-0.0112	-0.013	-0.0146
AD2	-0.0026	-0.0053	-0.0081	-0.0108	-0.0136	-0.0164	-0.019
AD3	0.0019	0.003	0.0035	0.0035	0.003	0.0021	0.001
AD4	-0.0028	-0.0052	-0.0073	-0.009	-0.0102	-0.0108	-0.0113

In above table 5.2 and table 5.3 deviations are calculated using numerical techniques. Based on deviation values deformation can be observed. Matching conditions are given in tables below. Based on values in tables winding can be categorized and totally deformed winding are send back to manufacturer for rewinding .Good match and close match winding are good in condition and poor match needs attention.

Here CCC represents overall cross correlation coefficient while CCC1, CCC2, CCC3 and CCC4 represents cross correlation over different sections. To observation deviation more clearly overall range is divided into sections. CCC1 shows deviation in 0 – 25kHz frequency range, CCC2 shows deviation in 25kHz – 50kHz frequency range, CCC3 shows deviation in

50kHz – 75 kHz frequency range, and CCC4 shows deviation in 75kHz – 100kHz frequency range.

Table 5.4 Matching condition for SD

	SD
Good Match	0.1 - 0
Close Match	0.2 - 0.1
Poor Match	>=0.3
Very Poor Match	1

Table 5.5 Matching condition for CCC

	CCC
Good Match	0. 95 - 1
Close Match	0.90 - 0.95
Poor Match	< 0.89
Very Poor Match	<=0

Table 5.6 Matching condition for MSE

	MSE
Good Match	0.01- 0
Close Match	0.05 - -0.01
Poor Match	>= 0.05
Very Poor Match	1

Table 5.7 Matching condition for AD

	AD
Good Match	0.001 - 0
Close Match	0.005 - 0.001
Poor Match	> =0.001
Very Poor Match	1

Table 5.8 Matching condition for ASLE

	ASLE
Good Match	0.05 - 0
Close Match	0.1 - 0.05
Poor Match	>= 0.1
Very Poor Match	1

Table 5.9 Matching condition for CSD

	CSD
Good Match	0.1 - 0
Close Match	0.15 - 0.1
Poor Match	>= 0.15
Very Poor Match	1

Table 5. 10 Matching condition for MM

	MM
Good Match	0.90 - 1
Close Match	0.75 - 0.90
Poor Match	<=0.75
Very Poor Match	0

5.3 Conclusion

Numerical technique makes SFRA observation simple and easy to understand. Matching ranges are given in tables with that one can distinguish winding as healthy, slightly deformed and totally deformed. Researches feel MSE underestimates or overestimates the deviation. ASLE take care of shortcoming of MSE. In some cases ASLE is better than SD and in some cases SD is better. Every technique has its unique feature and limitations to calculate deviation so while deciding deformation in coil more than one techniques should be verified. Still among these 7 techniques CCC, SD and ASLE are better to differentiate healthy and deformed coil.

Chapter 6

Conclusion

6.1 Summary of work done

Assessment of winding deformation is necessary for safe operation, better maintenance and for reliability of transformer.40 MVA Transformer with given specification [22] has been designed in FEM based MATLAB software and forces generated during normal condition, 1% axial shift in coil and 1% axial deformation has calculated.

A helical test coil is designed with given specification in MATLAB and also in ELECTNET. By creating deformation in each section of coil changed in basic parameter of coil i.e. self inductance, mutual inductance, series capacitance and ground capacitance are obtained. Each section of coil is axially and radialy deformed from 1% to 7% and their respective changed parameters have been calculated. Normal healthy coils parameter is also measured in FEM modeling of coil in MAGNET and ELECTNET. The obtained parameter of healthy coil and deformed coil are then feed in matlab coding to obtain SFRA. With SFRA matlab coding graphs of input current Vs frequency, resistance Vs frequency and reactance Vs frequency are obtained. In SFRA results (in each graph) two plots are there i.e. one plot is of reference normal healthy coil and other plot is of deformed coil. Graphical observation of deviation of two plots will indicate extent of deviation. SFRA is graphical method. Trained /experienced person is needed to observe small deviation clearly. SFRA test is performed on 5oo kVA transformer. Reference fingerprint of R phase Y phase and B phase are obtained with experiment. Numerical technique are good techniques which represents numerical value of deviation. Numerical techniques such as CCC, SD, ASLE, AD, MSE, MM and CSD are used to observe deviation in winding numerically. With numerical techniques observation of deviation becomes simple and easy. Deformed coil can easily be distinguished from normal/healthy coil. Assessment of winding deformation in power transformer is carried out.

6.2 Scope for Further Research

Study of SFRA is broad topic SFRA gives signature of transformer. Deviation in winding and location of faulty part in transformer can also be found out through SFRA. Deviation of graph in specific frequency represents fault in respective part of transformer. Artificial neural network can be used to the detect percentage of deformation in transformer winding from numerical technique.

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